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THE SPECIFIC HEAT, THERMAL CONDUCTIVITY, AND VISCOSITY OF LIQUID CESIUM

by

A. W. Lemmon, Jr., H. W. Deem, E. A. Eldridge, E. H. Hall,
J. Matolich, Jr., and J. F. Walling

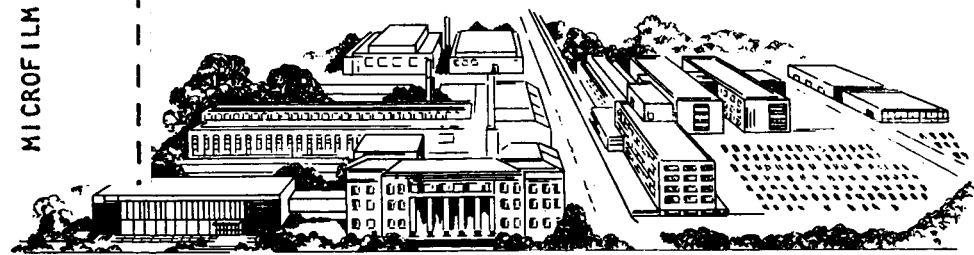
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TOPICAL REPORT

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Technical Management
NASA-Lewis Research Center
Cleveland, Ohio
Nuclear Power Technology Branch
James P. Couch

BATTELLE MEMORIAL INSTITUTE
505 King Avenue
Columbus, Ohio 43201

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ABSTRACT

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The specific heat, thermal conductivity, and viscosity of liquid cesium have been determined at temperatures to 2100 F. Specific heats were determined by measurements in a Bunsen ice calorimeter of the heat content of a cesium sample encapsulated in Nb-1Zr alloy. Thermal conductivities and electrical resistivities of cesium were measured in a steady-state, longitudinal-heat-flow apparatus. Corrections for the conduction of the container required that the thermal conductivities and electrical resistivities of the Nb-1Zr alloy also be measured. By finding the decrement of an oscillating cylinder partially filled with cesium, the desired viscosity values were computed from the theoretical relation.

Author

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INTRODUCTION AND SUMMARY

Under Contract NAS 5-584 with the National Aeronautics and Space Administration, Battelle has undertaken a program of research to obtain a number of properties of liquid cesium. NASA is concerned with this information because of its interest in cesium for possible space applications as a heat-transfer medium and as a working fluid in ion-propulsion devices. The current experimental program on liquid cesium has been concerned with measurements of the enthalpy (specific heat), thermal conductivity, and viscosity.

The enthalpy and specific heat of cesium from 0 to 1150 C and its heat of fusion at 28.52 C were determined by means of data obtained with a Bunsen ice calorimeter. The cesium was contained in Nb-1Zr alloy capsules for the measurements. Measured enthalpy values were corrected for the vapor. The values obtained for specific heats of cesium are:

$$C_s(\text{solid}) = 0.0559 \quad (0 \text{ to } 28.52 \text{ C})$$

$$C_s(\text{liquid}) = 0.0554 \quad (28.52 \text{ to } 100 \text{ C})$$

$$C_s(\text{liquid}) = 0.060 \quad (300 \text{ to } 1150 \text{ C})$$

The heat of fusion of cesium was determined to be 3.54 cal/g. Cesium appears not to behave as a normally defined liquid from about 100 to 300 C.

The thermal conductivity of liquid cesium was measured from 50 to 1150 C by the longitudinal-heat-flow, steady-state, comparative method. The cesium was contained in Nb-1Zr alloy containers. Thermal conductivities in Btu/(hr)(ft²)(F/ft) were 12.0 at 122 F and 5.4₉ at 2192 F, and in watt/(cm²)(C/cm) units were 0.20₈ at 50 C and 0.09₅ at 1200 C. The estimated experimental error is ± 5 per cent. There is a change in slope for the thermal conductivity curve at about 200 C.

Electrical resistivity of liquid cesium was measured when the thermal conductivity was measured; the values obtained, in microhm-cm, were 44 at 100 C (212 F), and 246 at 1100 C (2012 F).

The thermal conductivity of the Nb-1Zr alloy containing the specimen ranged from 29.2 to 37.2 Btu/(hr)(ft²)(F/ft) at 212 and 2012 F respectively [0.507 to 0.64₄ watt/(cm²)(C/cm) at 100 and 1100 C]. The electrical resistivity of the Nb-1Zr alloy ranged from 19.4 microhm-cm at 212 F (100 C) to 55.9 microhm-cm at 2192 F (1200 C).

The viscosity of liquid cesium from 30 to 1150 C was measured by the oscillating-cylinder method. The temperature dependence is similar to that exhibited by potassium in that the logarithm of the absolute viscosity is not a simple linear function of reciprocal temperature. Two linear equations can be used to represent the data as follows:

303 to 600 K (30 to 327 C):

$$\log \eta = \frac{252}{T} - 2.785 ,$$

with a standard deviation of ± 0.028 in $\log \eta$.

600 to 1423 K (327 to 1150 C):

$$\log \eta = \frac{400}{T} - 3.029 ,$$

with a standard deviation of ± 0.026 in $\log \eta$.

Viscosity η is in poises and T is in degrees K. Conversion to engineering units leads to these equations:

545 to 1080 R (85 to 620 F):

$$\log \eta = \frac{454}{T} - 0.401 ,$$

1080 to 2560 R (620 to 2100 F):

$$\log \eta = \frac{720}{T} - 0.645 .$$

Viscosity is in pounds per foot-hour and T is in degrees Rankine.

These results do not agree with earlier published data, being uniformly higher by a factor of about 60 per cent in the common temperature region. The earlier data find support in the fact that the extrapolated viscosity at the melting point is in agreement with semiempirical predictions. On the other hand, no experimental error of that magnitude can be found in the present measurements. Experimental steps designed to resolve the uncertainty are suggested.

Planned measurements to determine the thermal conductivity of cesium vapor were not performed because of the indeterminate performance of the dynamic bare-wire probe with potassium.

EXPERIMENTAL MATERIALS

(Joseph F. Walling)

Major problems in any experimental program to be performed on a reactive element at high temperatures relate to its purity and to the strength and compatibility of the material in which it must be contained. This section pertains to these problems.

Niobium-1 Zirconium Alloy

The decision was made, based primarily on the previous experience with potassium^{(1)*}, to fabricate from the Nb-1Zr alloy the test cells for the various items of equipment to be used for the measurements on cesium. Therefore, the needed items of the Nb-1Zr alloy were ordered from the most appropriate supplier. Handling and acceptance procedures were, in general, the same as those used previously in the potassium work. Further tests for surface soundness were performed on solid stock marked for use in equipment for measuring the thermal conductivity and heat capacity of liquid cesium. These pieces of material were bored out later to form rather thin-walled containers, which requires surface soundness in the original stock.

General acceptance tests for all Nb-1Zr stock and tubing consisted of a metallographic examination. All material was judged satisfactory by this technique. All solid stock came from the same lot, and chemical analyses were rendered by the supplier. Oxygen and nitrogen levels were well below tolerance limits. Special analyses for nitrogen and oxygen were not run on the tubing. Good previous experience with the same supplier and sufficient confidence in the metallographic examination were deciding factors against doing additional analyses.

In compliance with instructions, the supplier delivered stock which was treated only with a very light vapor blast or perhaps sharp centerless grind. The supplier performed ultrasonic tests on the material and found no indications which were cause for rejection.

Upon receipt at Battelle, this stock was lightly liquid honed and then examined for surface flaws by means of a dye penetrant. This examination revealed many surface imperfections, some of which were attributed to faults in a swaging die. It is believed that this was good evidence to indicate that no machining operations were performed which might have tended to obscure surface-connected cracks. All imperfections observed were surface pits, not cracks which would have justified rejection. Additional visual observation under a microscope indicated nothing to cause rejection of the original stock.

Although much effort was expended in these additional acceptance tests, they were insufficient to guarantee completely the adequate performance of the material. Indeed, no acceptance tests could be done to provide such a guarantee. Therefore, additional testing was performed as fabrication of the pieces proceeded. No imperfections were detected at any point.

Cesium

The matter of obtaining pure, analyzed, and properly sized ampoules of cesium suitable for direct loading into the various apparatuses was explored. Commercial suppliers were more amenable to accepting purity requirements for material purchased than they were 2 years ago when potassium was needed. Consequently, cesium was obtained from the supplier in a state of purity and in containers suitable for direct loading into the various pieces of apparatus.

*References are listed at end of report.

The general loading procedure used successfully for potassium⁽¹⁾ was selected for use with cesium as well. This consisted of breaking a glass ampoule containing the alkali metal under vacuum and delivering the filtered fluid to the desired apparatus. Consequently, measured quantities of cesium were needed in glass ampoules. This proved simple to obtain from suppliers.

Analysis of samples for foreign-metal content is rather simply carried out by emission spectrography in the visible region. This procedure was also used for potassium. The matter of analyses for carbon, nitrogen, and oxygen is considerably more difficult. Although carbon and nitrogen contents of commercial lots are generally so small as to be of no consequence for present purposes, the oxygen contamination cannot be ignored because of its effect on the container material. Moreover, oxygen is picked up easily from many sources.

It is believed that no procedure for determining a meaningful oxygen content of liquid cesium exists now. The best information available indicates that mercury amalgamation and butyl bromide techniques, sometimes used for sodium and potassium, fail totally when applied to cesium. The nature of this failure is that quantitative oxygen additions to aliquots cannot be accurately detected. Neutron-activation techniques have not progressed sufficiently to be reliable at low concentrations.

Because of these factors, contamination levels must be inferred by indirect measurement. A well-accepted technique for estimating total impurities is that of freezing-point depression. It was possible to obtain cesium from a supplier in large glass ampoules, each fitted with a resistance-thermometer well and a stainless steel agitating device. It was then possible to obtain freezing-point curves during agitation of the metal which had been sealed in this container. A representative curve is shown in Figure 1.

Freezing points of six ampoules were determined to be 28.52, 28.52, 28.53, 28.52, 28.54, and 28.52 C. The depressions indicated by these freezing points reflect total contamination. But, calculation of the absolute magnitude of contamination is not completely reliable for several reasons:

- (1) The freezing point of absolutely pure cesium is not known.
- (2) The freezing-point-depression constant is therefore unknown.
- (3) The correctness of the method generally used to determine freezing point and depression of a freezing point is questionable when applied to cesium.

The method generally used to determine freezing points has been extensively developed by Rossini.⁽²⁾ It involves determining the freezing point of a sample as varying fractions of it are frozen. It assumes an ideal liquid solution in equilibrium with absolutely pure solid. This assumption is questionable in present applications, but investigation in this area is beyond the program scope. It is nonetheless possible to infer several things in general:

- (1) The higher the freezing point the purer the sample.
- (2) The smaller the slope of the equilibrium portion of the curve, the purer the sample.

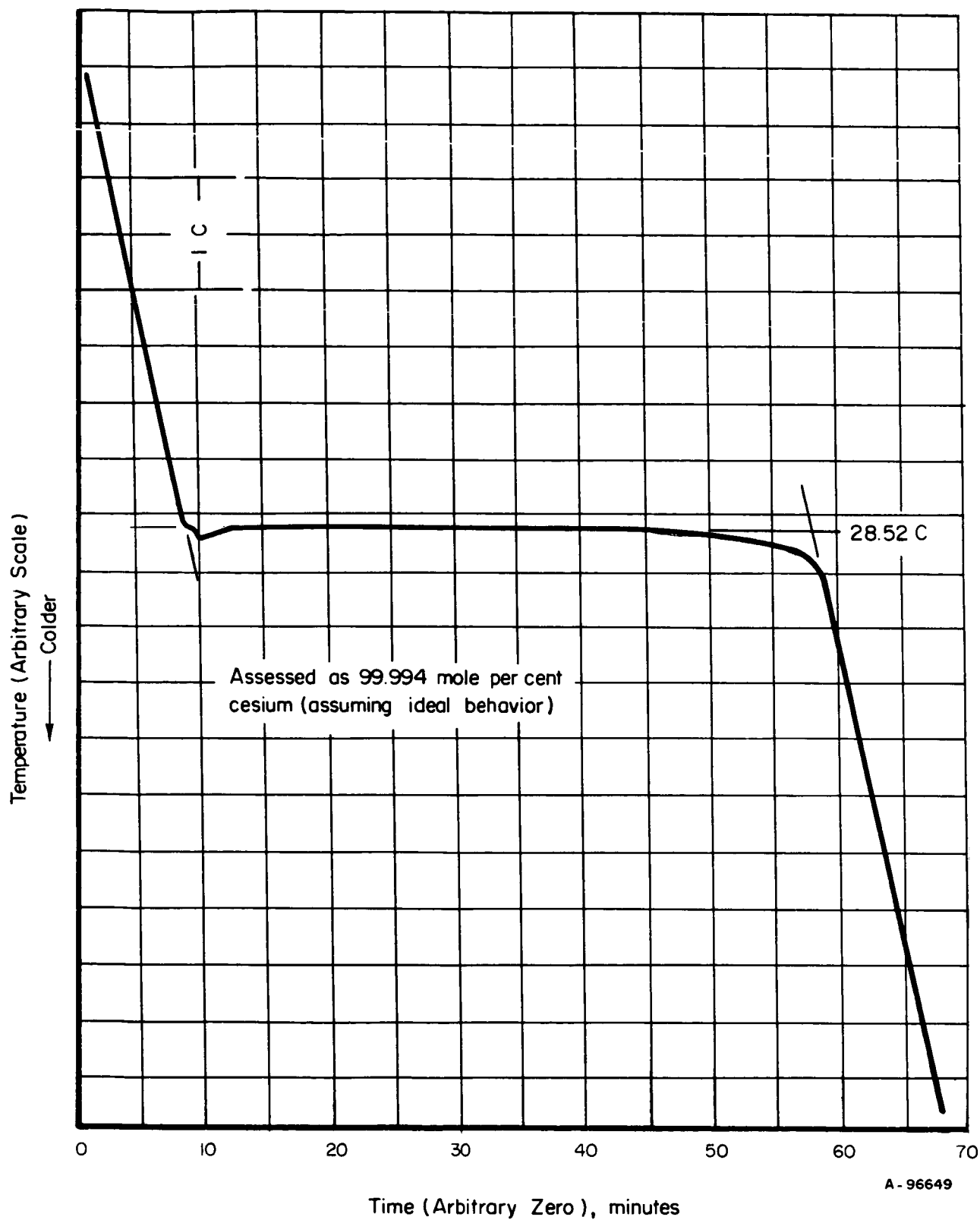


FIGURE 1. FREEZING POINT CURVE OBTAINED WHILE STIRRING THE CESIUM IN LARGE AMPOULE 2

The freezing points reported here are as high as or higher than those of any reliable reported measurements. Slopes of the equilibrium portion of all curves are virtually undetectable. A temperature difference of 0.05 C could be seen with ease. On the basis of ideal solution behavior, the supplier has estimated all samples to be 99.994 per cent cesium or better. Thus, all indications are of acceptable material in the six large ampoules.

It was not possible to determine the freezing points of the eight small ampoules. However, it is reasonable to infer their acceptability. Contamination can come from three sources:

- (1) The batch material and delivery-tube system.
- (2) The atmosphere contacting the metal.
- (3) Surface material in each individual ampoule.

In filling, all ampoules were fabricated and transferred while hot to an inert-gas-filled dry box which housed a cesium reservoir. Thus, the atmosphere was common to all ampoules. All ampoules were filled from the same cesium reservoir-delivery tube system. It is, therefore, reasonable to expect similar effects in all ampoules from these two sources of contamination. Significant problems with contamination by surfaces in individual ampoules would be reflected in erratic freezing points of the large ampoules. This is clearly not the case. Therefore, the similar handling of all ampoules makes it reasonable to infer approximate uniformity of the material supplied and acceptability of the cesium in the small ampoules on the basis of the acceptability of the cesium in the large ampoules.

Foreign-metal content has also been assessed by spectrographic techniques. A batch analysis from the supplier and results of a sample analyzed at Battelle are tabulated in Table 1.

TABLE 1. FOREIGN METAL CONTENT OF CESIUM

Amount, ppm			Amount, ppm		
Supplier,			Supplier,		
Element	Batch	Battelle	Element	Batch	Battelle
Al	<2	2	Ni	<2	5
Ag	--	1	Pb	<2	--
Ba	8	--	Si	<4	10
B	<18	--	Sn	8	--
Ca	18	3	Sr	<2	--
Cu	<2	10	Ti	<2	--
Cr	<2	--	Tl	<2	--
Fe	<14	2	Li	18	--
Mg	5	1	Na	<16	20
Mn	5	--	K	7	15
Mo	--	1	Rb	35	20

Differences between these analyses are not important for the current experimental program. Sampling error in the one sample analyzed at Battelle could probably explain many discrepancies. However, foreign-metal content is certainly at a satisfactorily low level. Therefore, the cesium was judged acceptable by all standards imposed.

SPECIFIC HEAT AND HEAT OF FUSION

(E. A. Eldridge and H. W. Deem)

The measurement of the specific heat and heat of fusion of cesium is of interest because of cesium's possible use as a working fluid in high-temperature nuclear electric-generating systems. The present measurements of the heat content of cesium follow closely the method and apparatus used in an earlier phase of this program for potassium⁽³⁾, except for a different calorimeter furnace used at temperatures above about 700 C. A graphite-tube furnace with a purified argon atmosphere was used for the measurements on potassium. However, in those previous measurements there was a problem of capsule oxidation at elevated temperatures with an attendant increase in capsule weight and enthalpy. Therefore, a vacuum furnace operating at about 1×10^{-5} mm of mercury was used to heat the cesium capsules to temperatures above 700 C. Temperatures were measured with an optical pyrometer that was calibrated for the effect of the furnace window and sighted on the capsule through a small hole in the tantalum heater. Provision was made to drop the capsules from the furnace by melting a small supporting wire by resistance heating.

They were made following the second design used for the potassium capsules.⁽³⁾ The capsules retained their bright shiny appearance and did not gain weight when heated in the vacuum furnace.

Procedures and Results

Three different types of capsules were dropped: (1) a capsule containing a material of known heat content, (2) a Nb-1Zr capsule containing the cesium specimen, and (3) an empty Nb-1Zr capsule of about the same size and weight of the specimen capsule.

Al₂O₃ from the National Bureau of Standards was dropped as a material of known heat content in two capsules. One capsule, of Nichrome V, was dropped at temperatures to 651.4 C in the argon atmosphere furnace, and a tantalum capsule was used at higher temperatures in the vacuum furnace.

Table 2 shows the values obtained for the Al₂O₃ standard at various temperatures and also values at the same temperatures from an equation representing the data of Ginnings and Furukawa.⁽⁴⁾ The agreement was good, reaching a maximum difference of 0.8 per cent at 977 C, the highest temperature checked.

TABLE 2. ENTHALPY VALUES FOR Al_2O_3 ^(a)

Temperature, t, C	Measured H_t , cal/g	Reference H_t ^(b) , cal/g	Difference, per cent of reference H_t
<u>Nichrome V Capsule, Argon Atmosphere</u>			
190.8	40.1	40.3	-0.5
193.7	40.9	41.0	-0.2
394.9	92.7	93.2	-0.5
650.2	164.7	165.0	-0.2
650.7	164.8	165.1	-0.2
651.4	165.6	165.3	+0.2
<u>Tantalum Capsule, Vacuum</u>			
786.0	203.6	204.6	-0.5
977.0	258.2	260.4	-0.8

(a) National Bureau of Standards Al_2O_3 in Nichrome V and Tantalum Capsules.

(b) From equation in Reference (4).

TABLE 3. AS-DROPPED ENTHALPY VALUES AND VALUES CORRECTED FOR CESIUM VAPOR CONDENSATION

Temperature, C	Enthalpy H_t , cal/g		Correction, per cent of corrected H_t
	As Dropped	Corrected for Vapor Condensation ^(a)	
620.8	36.5	36.5	0
792.0	48.5	48.4	0.20
905.0	56.2	56.0	0.36
978.0	59.5	59.3	0.34
1084.0	65.1	64.9	0.31
1162.0	70.8	70.5	0.43

(a) By the method of Reference (5).

In work with potassium, the enthalpy was corrected to compensate for the condensation of potassium vapor from the space above the liquid in the capsule. ⁽³⁾ An equation by Osborne⁽⁵⁾ used for this purpose for potassium gave a maximum correction of 0.2 cal/g in the total of 238 cal/g, which was considered negligible. However, the vapor-condensation correction applied to cesium is significant because, in comparison with potassium, cesium's lower enthalpy more than offsets its higher density.

In using the vapor correction equation of Osborne, it was necessary to insert values for the vapor pressure of cesium. The following vapor-pressure-temperature relation for cesium reported by Tepper et al.⁽⁶⁾ was used in calculating the vapor corrections:

$$\log_{10} P = \frac{-6631.74}{T} + 3.9011 \quad (1)$$

where

P = pressure, atmospheres absolute

T = temperature, degrees Rankine.

Cesium vapor pressure data by Ewing⁽⁷⁾, received too late for use in the calculations are represented by the following expression:

$$\log_{10} P = 5.89055 - \frac{6972.7}{T} - 0.542 \log_{10} T \quad (2)$$

where

P = pressure, atmospheres absolute

T = temperature, degrees Rankine.

The cesium vapor pressure from Ewing's⁽⁷⁾ relation are higher than those calculated from Tepper's⁽⁶⁾ Equation (1) by about 6 per cent (31 psi) at 1300 C and 28 per cent (37 psi) at 1000 C.

Table 3 shows the cesium enthalpy data, both as originally obtained from the calorimeter and as corrected for vapor condensation. The values as corrected for vapor condensation also appear later in Table 4.

Enthalpy of Solid and Liquid Cesium

Solid Cesium. Table 4 shows observed and equation enthalpy data for cesium. The enthalpy data for solid cesium shown in Table 4 were fitted with an equation of the form $H_t = A + Bt$ (H_t = enthalpy from 0 to 28.52 C).

The observed enthalpy data in Table 4 were fitted with the following equation:

$$H_t(\text{solid}) = 0.0559t \quad (0 \text{ to } 28.52 \text{ C}) . \quad (3)$$

TABLE 4. ENTHALPY OF CESIUM

Temperature, C	Enthalpy, H_t , cal/g		
	Data(a)	Derived Values(b)	Residuals
0	0	0	0
22.3	1.26	1.25	+0.01
25.7	1.41	1.44	-0.03
26.7	1.52	1.49	+0.03
28.52 (solid)	--	1.59	--
Heat of fusion	--	3.54	--
28.52 (liquid)	--	5.13	--
30.0	5.21	5.21	0
94.1	8.60	8.76	-0.16
98.7	9.17	9.02	+0.15
195.7	15.4	--	--
200.8	15.5	--	--
291.3	18.6	18.0	+0.6
452.2	27.1	27.6	-0.5
617.5	37.4	37.6	-0.2
620.8	36.5	37.8	+1.3
792.0	48.4	48.0	+0.4
905.0	56.0	54.8	+1.2
978.0	59.3	59.2	+0.1
1084.0	64.9	65.5	-0.6
1162.0	70.5	70.2	+0.3

(a) Data contain cesium vapor condensation correction.

(b) Equation (3) H_t (solid) = $0.0559t$ (0 to 28.52 C).

Equation (4) H_t (liquid) = $3.55 + 0.554t$ (28.52 to 100 C).

Equation (5) H_t (liquid) = $0.5 + 0.06t$ (300 to 1150 C).

Liquid Cesium. Table 4 also shows experimental enthalpy data for liquid cesium. An equation of the form $H_t = A + Bt$ (H_t = enthalpy from 0 to t C) was selected to represent the enthalpy data as a function of temperature over the temperature range from 28.52 to 100 C.

The region from about 100 to 300 C has not been covered by an equation because more enthalpy values in this region would be required to obtain specific heats through what appears to be a region of anomalous behavior (see "Discussion").

An appraisal of an enthalpy-versus-temperature plot of the data (Figure 2) from 291.3 to 1163 C indicated that an equation of the form $H_t = A + Bt + Ct^2 + Dt^3$ (H_t = enthalpy from 0 to t C) would adequately represent the data. The least squares analysis fitted the experimental data between the extremes of -0.87 and +0.77 per cent. The constants were only slightly overdetermined.

Unfortunately, the first derivative of the third-order enthalpy equation obtained in this way (as predicted by a visual appraisal) gave specific heats that exhibited a trend with temperature opposite to that expected for alkali metals. The specific heat increased with temperature from 300 to about 700 C, after which it decreased. The opposite trend would be expected. For example the curve for liquid potassium⁽³⁾ decreased from 0.194 at 75 C to 0.183 at 400 C and then increased to 0.245 cal/(g)(C) at 1150 C. Douglas et al.⁽⁸⁾ show a similarly shaped curve for potassium.

Evans et al.⁽⁹⁾ of the National Bureau of Standards present a brief discussion of thermodynamic properties of the alkali metals and include literature data on the specific heats of lithium, sodium, and potassium. The values for lithium show a gradual decrease with temperature while those for sodium and potassium first decrease with temperature to about 600 C and then increase.

Although an exact error analysis has not been made for the measured cesium enthalpy values, an appraisal of the experimental conditions indicates that the individual measured values may be in error by as much as 7 per cent. This unusually high error for drop calorimetry results from (1) the relatively low enthalpy and specific heat of cesium (about 1/3 those of potassium), and (2) the heavy capsule wall (a 0.045-inch-thick wall was considered to be necessary for the cesium capsule compared with 0.020-inch-thick walls for the first potassium capsules). It is estimated that the maximum error of the measured enthalpy of the empty capsule is ± 0.5 per cent, a value that seems reasonable from the Al_2O_3 data in Table 2. A similar maximum error of ± 0.5 per cent can be justified for the enthalpy of the capsule plus cesium. If these errors are assumed to occur in opposite directions, the cesium enthalpy which is the difference could be in error by 1 per cent of the total capsule plus cesium enthalpy. Since the total enthalpy of capsule plus cesium is about 7 times that of the cesium, the enthalpy of the cesium obtained by differences could be in error by as much as 7 times 1 per cent, or 7 per cent.

In view of the uncertainties in the enthalpy data and their treatment, a first-order equation for the enthalpy is presented rather than the third-order equation. Also, a third-order equation would result in a trend in specific heat opposite to that observed for the other alkali metals.

The enthalpy equations for liquid cesium are:

$$H_t(\text{liquid}) = 3.55 + 0.0554t \quad (28.52 \text{ to } 98.7 \text{ C}) \quad (4)$$

$$H_t(\text{liquid}) = 0.5 + 0.06t \quad (291.3 \text{ to } 1163 \text{ C}) . \quad (5)$$

Figure 2 shows a plot of the experimental enthalpy data as given in Table 4 and the enthalpy Equations (3), (4), and (5) above. Figure 2 also shows the least squares fit to data from about 300 to 1150 C.

Figure 3 is a plot showing calculated enthalpy values by Tepper et al.⁽⁶⁾ and by Stull and Sinke⁽¹⁰⁾, and experimental data by Achener⁽¹¹⁾, as compared with the present work. The Battelle enthalpy data are lower than the other data by roughly 3 cal/g over the temperature ranges where comparisons can be made.

Specific Heat of Solid and Liquid Cesium

For practical purposes the specific heat of solid cesium is given by the first derivative of Equation (3) and is

$$C_s(\text{solid}) = 0.0559 \text{ cal/(g)(C)} \quad (0 \text{ to } 28.52 \text{ C}) . \quad (6)$$

The heat capacity of liquid cesium along the saturation path is $C_s = \frac{dH}{dt} - v \frac{dP}{dt}$ where v is the specific volume, P is the vapor pressure, and H is H_t of Equations (4) or (5). The product $v \frac{dP}{dt}$ was numerically evaluated at a series of temperatures using the density data of Cochran⁽¹²⁾ and the vapor pressure data of Tepper⁽⁶⁾. The $v \frac{dP}{dt}$ values were approximately 0.1 per cent of the $\frac{dH_t}{dt}$ term at 600 C, 0.6 per cent at 800 C, 1.6 per cent at 1000 C, and 2.7 per cent at 1150 C.

A $v \frac{dP}{dt}$ term which would have a value as large as the 2.7 per cent value at 1150 C would normally be taken into consideration in deriving specific heat values. However, in this instance it has been neglected because it would introduce a questionable negative slope to the specific heat curve.

Neglecting the $v \frac{dP}{dt}$ term, the specific heat of liquid cesium is approximated by the first derivatives of Equations (4) and (5) as follows:

$$C_s(\text{liquid}) = 0.0554 \text{ cal/(g)(C)} \quad (28.52 \text{ C to } 100 \text{ C}) \quad (7)$$

$$C_s(\text{liquid}) = 0.060 \text{ cal/(g)(C)} \quad (300 \text{ to } 1150 \text{ C}) . \quad (8)$$

Shapiro and Meisl⁽¹³⁾ report a straight line specific heat value of 0.0572 cal/(g)(C) from 500 to 1150 C.

Since a straight-line representation for the enthalpy averages errors and serves to diminish them somewhat, and since no exaggeration results in evaluating the derivative for a straight-line function, the maximum error for the specific heat is estimated as ± 5 per cent.

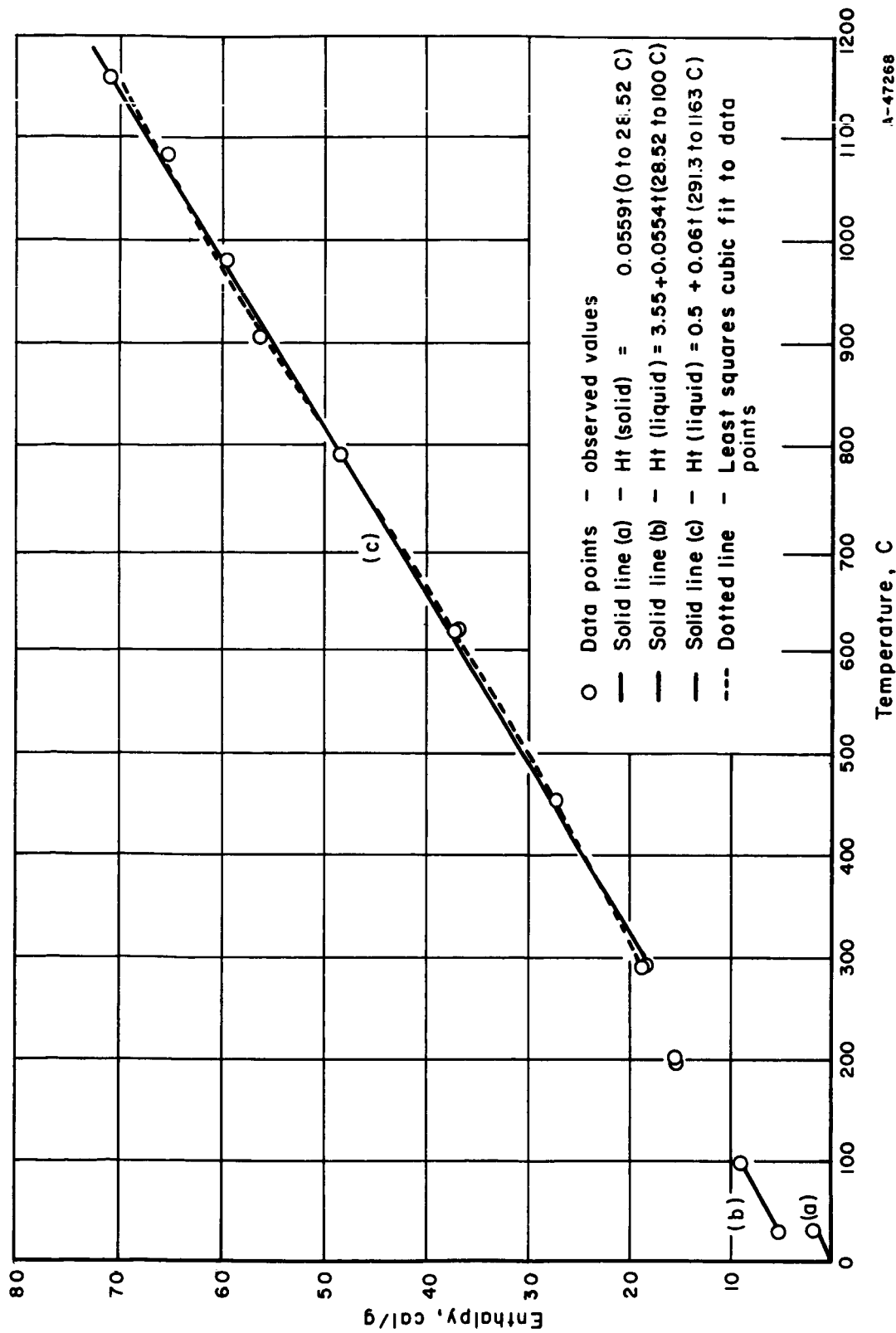
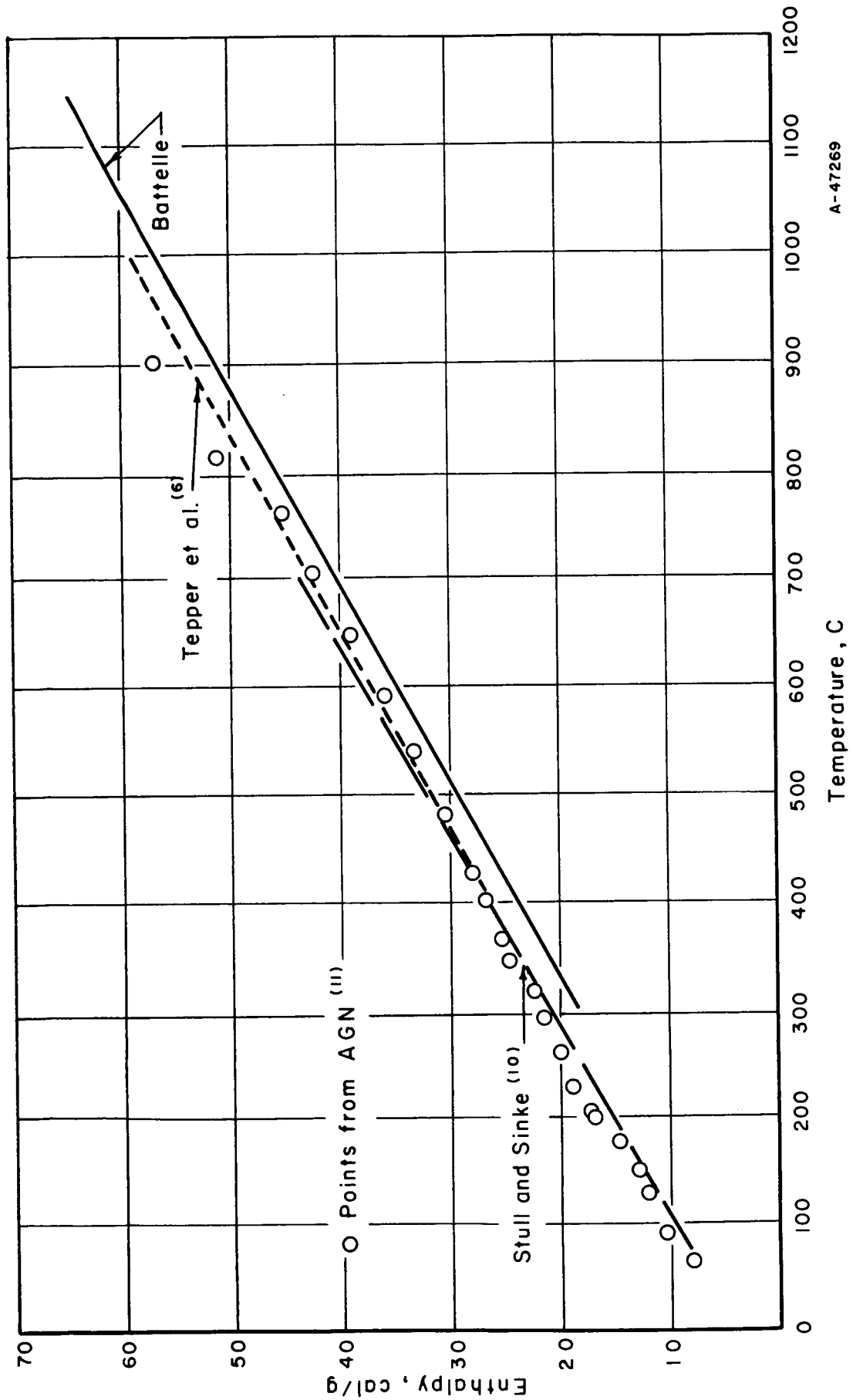


FIGURE 2. ENTHALPY OF SOLID AND LIQUID CESIUM



A-47269

FIGURE 3. ENTHALPY, LITERATURE VALUES COMPARED WITH PRESENT WORK

Heat of Fusion of Cesium

The melting point of cesium is given as 28.52 C. (See "Experimental Materials" section of this report.) The heat of fusion of cesium is obtained as the difference between the calculated enthalpy of solid cesium at 28.52 C, using Equation (3), and the calculated enthalpy of liquid cesium at the same temperature, using Equation (4). The heat of fusion is calculated as 3.54 cal/g. This compares with the value of 3.84 cal/g reported by Weatherford et al. (14).

Discussion

Somewhere in the temperature range of 100 to 300 C, the cesium does not behave as expected. This anomalous behavior seems to be real and has been observed by others. Tepper et al. (6) show it in their data on enthalpy of cesium. The plotted data points of Achener (11) in Figure 3 show an inflection at about 200 C. The thermal-conductivity measurements of liquid cesium (described elsewhere in this report) show a change of slope in the thermal conductivity-versus-temperature for liquid cesium at about 200 C. The electrical resistivity-versus-temperature data for liquid cesium, show scatter in this region. While a curve drawn within the apparent error bands does not show an inflection in this temperature range, it is believed that the individual data points indicate that an anomaly exists.

It is clear that more data than are presently available would be required before an adequate study could be made of the apparent anomaly.

THERMAL CONDUCTIVITY AND ELECTRICAL RESISTIVITY

(J. Matolich, Jr., and H. W. Deem)

Thermal conductivity is an important property of liquid metals used as heat-transfer and working fluids for nuclear electric-power generation for space applications. The present thermal conductivity measurements on liquid cesium are a continuation of the program which started with similar measurements on liquid potassium. (15)

Liquid Cesium

The present measurements on cesium followed closely the method and apparatus used for potassium except that the specimen container used for cesium had walls about 0.040 inch thick as compared with 0.020 inch in containers for potassium. There was evidence that potassium had permeated and penetrated the chamber walls in sufficient quantity to force a termination of the measurements. In the current work, no evidence of cesium leakage was observed.

The same arrangement and numbering of thermocouples was used for the cesium measurements as described for the measurements on potassium (15). There were seven thermocouples on the thin-walled section of the specimen container, numbered 1 through

TABLE 5. OBSERVED THERMAL CONDUCTIVITY OF CESIUM

Temperature, C	Thermal Conductivity, watt/(cm)(C/cm)	Run No. - Equilibrium No. (a)	Thermocouple Section(b)
22	0.371(c)	A-7	6-7
64	0.219	A-7	4-6
68	0.209	A-2	6-7
102	0.211	A-2	5-6
118	0.244	A-7	3-4
125	0.206	A-1	6-7
150	0.233	A-7	2-3
152	0.212	A-1	5-6
152	0.210	A-2	4-5
171	0.234(d)	A-7	1-2
174	0.196	B-1	6-7
178	0.190	B-4	6-7
183	0.183	B-2	6-7
191	0.207	A-1	4-5
209	0.204	A-3	6-7
215	0.204	B-1	5-6
217	0.223(d)	A-2	3-4
220	0.211	B-4	5-6
266	0.700(d)	A-1	3-4
270	0.186	A-3	5-6
276	0.194	B-1	4-5
283	0.199	B-4	4-5
287	0.0352(d)	A-2	2-3
328	0.173	A-4	6-7
347	0.0204(d)	A-1	2-3
357	0.197	B-1	3-4
364	0.192	B-2	5-6
366	0.210	B-4	3-4
367	0.0182(d)	A-2	1-2
412	0.162	A-4	5-6
414	0.0162(d)	A-1	1-2
418	0.185	B-1	2-3
428	0.200	B-4	2-3
429	0.176	A-3	4-5
459	0.198	B-1	1-2
466	0.172	B-2	4-5
468	0.209	B-4	1-2
546	0.141	A-4	4-5
585	0.0885(d)	A-3	3-4
605	0.168	B-2	3-4
659	0.157	A-5	6-7
683	1.599(d)	A-3	1-2
691	0.279(d)	A-3	1-2
712	0.150	B-2	2-3
714	0.148	A-5	4-5
783	0.0447(d)	A-4	3-4

TABLE 5. (Continued)

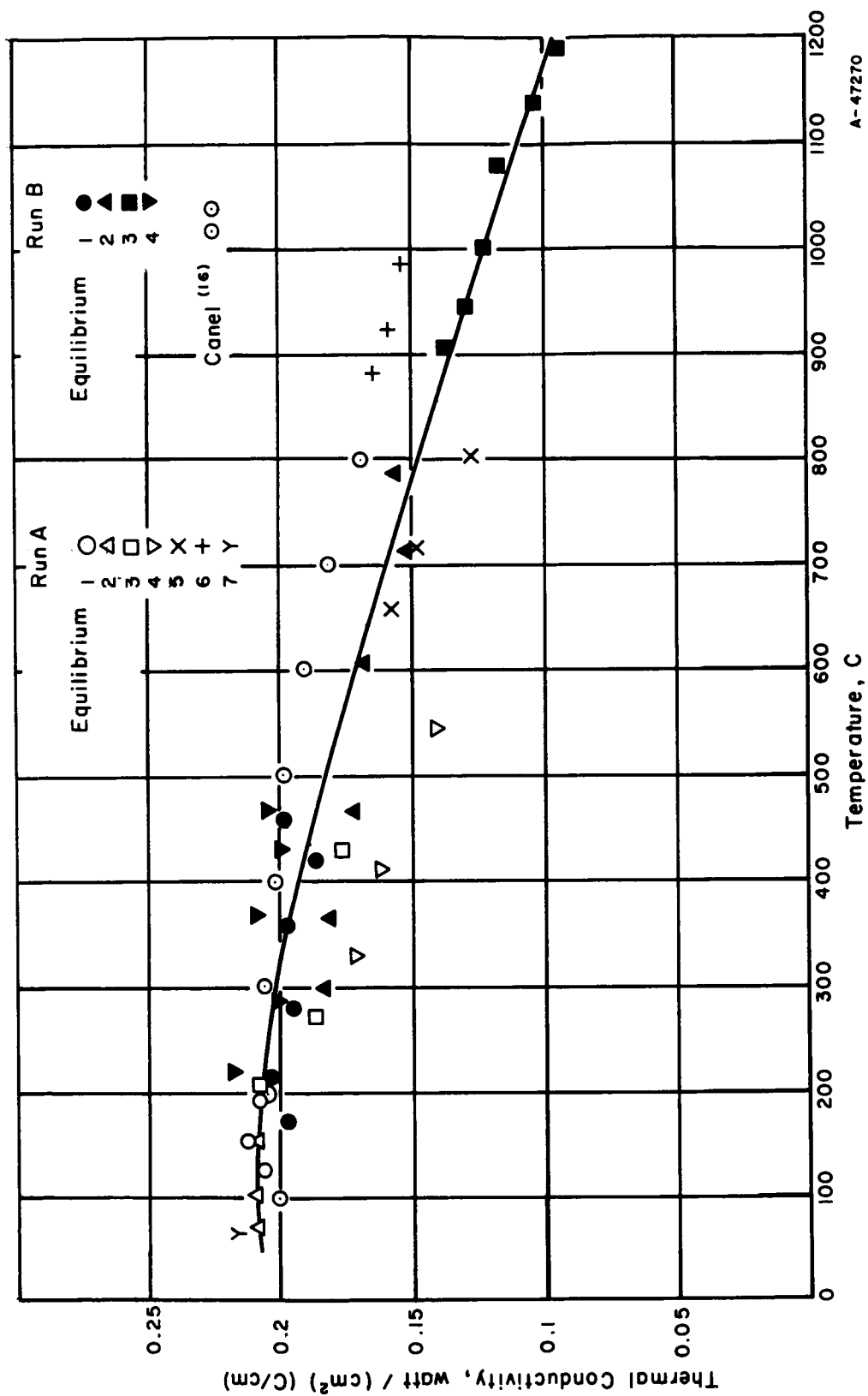
Temperature, C	Thermal Conductivity, watt/(cm)(C/cm)	Run No. - Equilibrium No. (a)	Thermocouple Section(b)
784	0.156	B-2	1-2
802	0.127	A-5	4-5
884	0.164	A-6	6-7
907	0.137	B-3	6-7
923	0.158	A-6	5-6
934	2.167(d)	A-4	2-3
944	0.130	B-3	5-6
954	0.0453(d)	A-5	3-4
985	0.154	A-6	4-5
989	0.135(d)	A-4	1-2
1002	0.121	B-3	4-5
1056	0.539(d)	A-5	2-3
1075	0.732(d)	A-5	1-2
1081	0.116	B-3	3-4
1088	0.0588(d)	A-6	3-4
1141	0.1034	B-3	2-3
1156	1.142(d)	A-6	2-3
1163	1.624(d)	A-6	1-2
1183	0.948	B-3	1-2

(a) The letter A or B designates Run A or Run B. The numbers from 1 to 7 indicate the equilibrium number taken during the run, listed in chronological order.

(b) The thermocouple section designates the two thermocouples bounding a section of the specimen container over which a temperature gradient was measured and for which a thermal conductivity was calculated at the mean specimen temperature. There were seven specimen thermocouples numbered 1 through 7, in order of decreasing temperature.

(c) Specimen in section was mostly solid.

(d) Value rejected because thermocouples 1, 2 and/or 3 in Run A were involved. See text.



7 starting with Thermocouple 1 at the top or hottest end of the specimen and running in numerical order downward and cooler to Thermocouple 7. Thermocouples 8, 9, 10, and 11 were in the solid portion of the Nb-1Zr rod used as the thermal conductivity reference material, and were in order of decreasing temperature. Thermocouples 1 through 7 on the specimen container wall were not equispaced. The distance between Thermocouples 3 to 4, and 4 to 5 were twice as great as the distances between 1 to 2, 2 to 3, 5 to 6, and 6 to 7. These distance relations assist in understanding the thermal conductivity values for different sections of the specimen described later.

Calculations and Results

Two thermocouple assemblies were used in the course of the thermal conductivity measurements, with several thermal equilibria being obtained for each assembly. The measurements made with the two assemblies are referred to as Run A and Run B, with the various thermal equilibria designated by a number following the run letter.

Thermal Conductivities. The data were calculated as described in BATT-4673-T6⁽¹⁵⁾. Table 5 shows the thermal conductivity values calculated from data obtained in Runs A and B. Figure 4 is a plot of the data in Table 5 excepting values in Run A that resulted from temperatures measured by Thermocouples 1, 2, or 3 which showed considerably more scatter than the data obtained when using the other thermocouples. The data from Run B appear to be more representative of the thermal conductivity of cesium than those from Run A and are considered to be more reliable. The curve in Figure 4 was visually fitted to the observed data, giving preference to the data from Run B.

Table 6 shows thermal conductivity values of liquid cesium in cgs and English units as read from the curve in Figure 4. A comparison of the present values with those calculated by CANEL⁽¹⁶⁾ using the Lorenz relation is shown also in Table 6.

TABLE 6. INTERPOLATED THERMAL CONDUCTIVITY OF CESIUM

Temperature, C	Thermal Conductivity, watt/(cm ²)(C)/cm		Temperature, F	Thermal Conductivity, Btu/(hr)(ft ²)(F/ft)	
	This Work	CANEL(16)		This Work	
50	0.208		122	12.0	
100	0.208	0.200	212	12.0	
200	0.207	0.205	392	12.0	
300	0.202	0.205	572	11.7	
400	0.193	0.202	752	11.2	
500	0.182	0.198	932	10.5	
600	0.170	0.190	1112	9.8 ₂	
700	0.158	0.180	1292	9.1 ₃	
800	0.146	0.168	1472	8.4 ₃	
900	0.134		1652	7.7 ₄	
1000	0.122		1832	7.0 ₅	
1100	0.10 ₉		2012	6.3 ₀	
1200	0.09 ₅		2192	5.4 ₉	

Electrical Resistivities. The Battelle apparatus is equipped to make electrical-resistivity measurements of cesium concurrently with the thermal conductivity measurements, using the thermal conductivity apparatus and specimen. Figure 5 is a plot of observed electrical resistivity versus temperature. Table 7 shows interpolated electrical resistivity values for liquid cesium taken from the curve shown in Figure 5 and a comparison with the values obtained by CANEL⁽¹⁶⁾.

TABLE 7. INTERPOLATED ELECTRICAL RESISTIVITY
OF LIQUID CESIUM

Temperature, C	Electrical Resistivity, microhm-cm	
	Battelle	CANEL ^(a)
50		
100		43
200	55	56
300	67	68
400	80	81
500	96	96
600	114	113
700	134	134
800	155	158
900	179	186
1000	208	
1100	246	

(a) Calculated from $\rho = 34,383 + 1,124 \times 10^{-1}t - 2,869 \times 10^{-5}t^2 + 1,007 \times 10^{-7}t^3$, as given in CANEL⁽¹⁶⁾.

Discussion

Several considerations concerning Runs A and B are necessary to evaluate the data.

Run A. Seven thermal equilibria were obtained with the first thermocouple assembly measurements, referred to as Run A. Pt vs. Pt-10Rh thermocouples were used to measure the specimen temperatures during Run A. The thermocouple wires were arranged to encircle the specimen container at the desired elevation and the wires near the bead were welded at intervals to the specimen container. The wires did not touch the specimen container between the last weld and where they left their elevation to go down and out of the chamber. From the last weld they were in a uniform temperature plane for a sufficient distance to minimize heat transfer to or from the temperature measuring point.

Difficulties were encountered during Run A in obtaining reasonable thermal conductivity and electrical resistivity values for sections of the specimen which involved Thermocouples 1, 2, and 3. It is difficult to assign a reason for the wide scatter of data resulting from calculations involving these thermocouples. It is known from ohm-meter continuity checks that at least one part of each thermocouple was in metallic

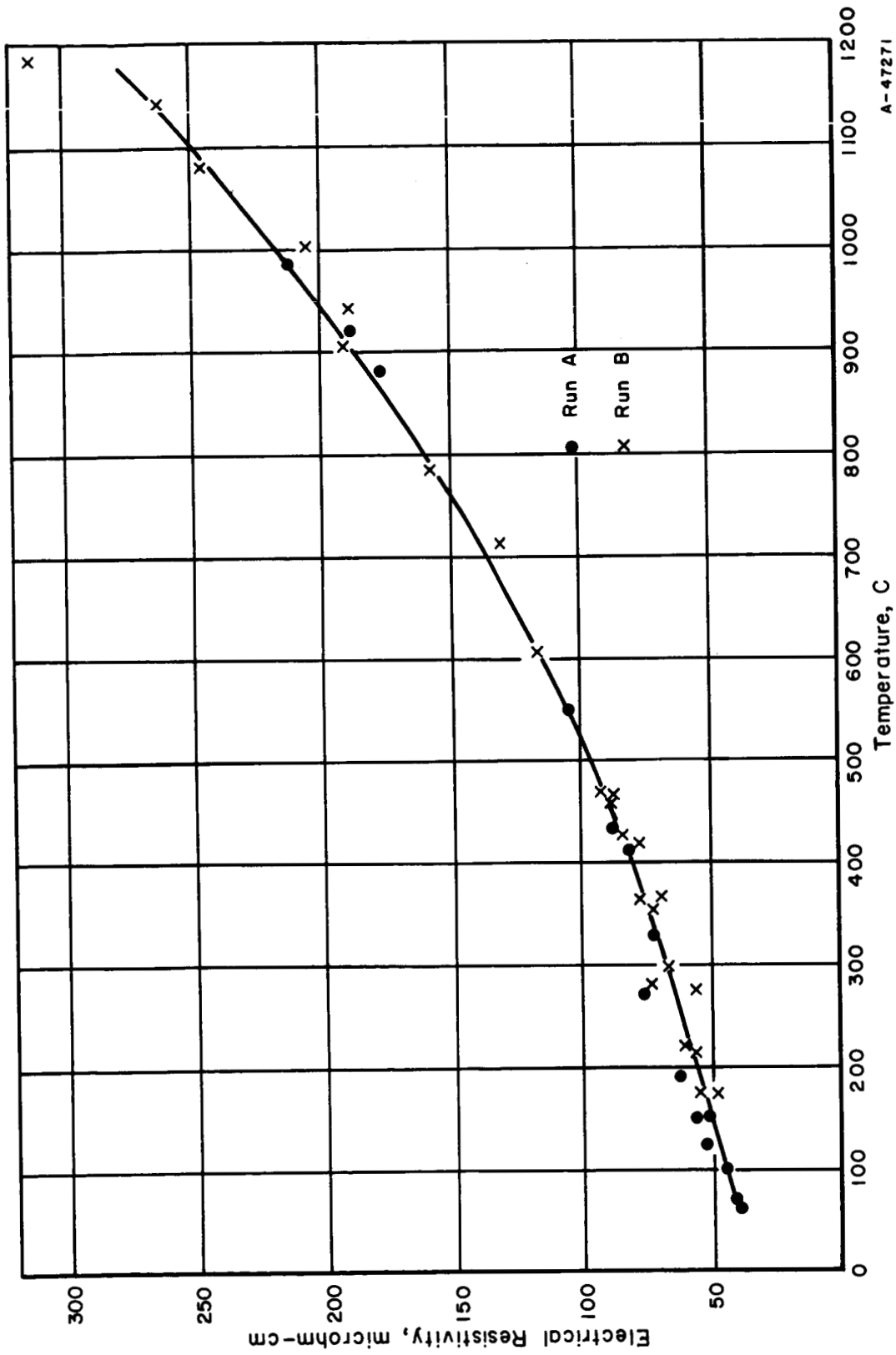


FIGURE 5. ELECTRICAL RESISTIVITY OF CESIUM

contact with the specimen during each of the measurements, and also that the thermocouple circuits were continuous. Possible reasons for the very wide scatter of calculated thermal-conductivity values from Thermocouples 1, 2, and 3 (from 27.2 to 0.016 as shown in Table 5) include:

- (1) The thermocouple beads may have become detached from the specimen container and moved in location with respect to the container because of differential thermal expansions in the assembly. Electrical contact could have been made by only one wire of the thermocouple but not at the bead. Errors of temperature measurement because of bead mislocation are not believed to be responsible for all of the data scatter encountered.
- (2) The possibility of thermocouple-bead contamination was considered. It is considered unlikely that the thermocouples could have become contaminated to the degree necessary to produce the wide variation of results at the temperatures at which they occurred. A check during Run A of the beads and after Run A of the wires (but not the beads) of Thermocouples 1 and 2 showed them to be within tolerance.
- (3) The abnormally low thermal conductivities could possibly result from failure of the melted cesium to wet the container walls in the regions of Thermocouples 1, 2, and 3. The presence of a high thermal resistance coating on the wall could insulate the melt thermally and electrically from the wall, causing the measured heat flow to be almost entirely in the wall, with a consequent large temperature gradient and low calculated thermal conductivity.
- (4) The abnormally high thermal conductivities could possibly result from a turbulence and convective heat flow in the upper part of the specimen, associated with a "conditioning" of the liquid metal and/or container surface during the first heating, which would add to the conductive heat flow. If such a condition existed, it was only during the first heating (Run A), because all thermocouples and sections of the specimen acted normally during Run B. The mechanism by which this could take place is not understood.

Because of the wide scatter of data resulting from the use of Thermocouples 1, 2, and 3, values derived from their readings were not used. They do, however, appear in Table 5.

Run B. Run B differed from Run A in the following respects:

- (1) The Pt vs. Pt-10Rh thermocouples used in Run A were replaced with Pt-30Rh vs. Pt-6Rh thermocouples. These thermocouples are known to be much less affected by contamination because of rhodium initially in the platinum leg. It is the first small addition of a contaminant in the pure platinum leg that produces the greatest change in calibration. With 6 per cent rhodium present, the addition of a small amount of a contaminant is not significant.

- (2) The thermocouple wires were welded to the specimen container in much the same manner as described for Run A, except that the bead was snipped off. Thus the thermocouple "bead" in effect included the specimen.
- (3) It is believed that the temperature excursion during Run A may have cleaned the container wall and the cesium wet the wall better during Run B than in Run A. Radiographs taken before and after Run A showed that the depression of the meniscus for cesium at the chamber wall was not as large as than for potassium at the wall. (15)

For the reasons enumerated, the data from Run B are considered more reliable than those from Run A, and are therefore weighted more heavily in drawing the thermal conductivity-versus-temperature curve shown in Figure 4. All data points for Equilibria 1, 2, 3, and 4 of Run B are plotted in Figure 4, which was not possible for Run A.

The thermal conductivity plot in Figure 4 indicates that the property is sensitive as indicated by a change in slope, to an apparent anomaly in the region of 200 C. This anomaly was also mentioned in connection with enthalpy, specific heat, and electrical resistivity measurements of cesium.

There was evidence after Run A that the argon pressure used outside the specimen chamber was insufficient to balance the vapor pressure of cesium inside the chamber. At the hottest part of the thin-walled specimen chamber, just above Thermocouple 1, the chamber diameter was found to have increased about 0.004 inch during Run A. As the argon external pressure was carefully balanced against the cesium vapor pressure (as calculated from Equation (1)⁽⁶⁾), it is suspected that Equation (1) gives vapor pressures in error on the low side. Because of this suspicion the argon pressure was arbitrarily increased about 25 psi during Run B.

The specimen chamber was examined after Run B. There was much less oxide on the Nb-1Zr surface after Run B than there was after Run A, indicating that there was less outgassing of the insulation during its second heating. All thermocouples appeared to be firmly welded or pinned in place. There was no measurable increase in the diameter of the thin-walled specimen container during Run B. This indicates that the arbitrary increase in argon pressure of 25 psi during Run B over that in Run A more nearly balanced the cesium vapor pressure than did the values by Tepper⁽⁶⁾ used for Run A.

Nb-1Zr Alloy

As explained in BATT-4673-T6⁽¹⁵⁾ it was necessary to measure the thermal conductivity of the Nb-1Zr bar from which the specimen container was made because a solid section of the rod is used as a reference standard. The measurements were made as described in Reference 15.

Table 8 shows interpolated thermal conductivity values of the present Nb-1Zr alloy compared with the values previously reported in BATT-4673-T6⁽¹⁵⁾ for the lot used with potassium. The values for the present lot are seen to be higher than the former lot by 2.6 to 6.5 per cent.

TABLE 8. INTERPOLATED THERMAL CONDUCTIVITY OF Nb-1Zr ALLOY

Temperature, C		Present Lot Used for Cesium Watt/(Cm ²)(C/Cm) Btu/(Hr)(Ft ²)(F/Ft)		Thermal Conductivity		Difference, per cent of previous lot
				Previous Lot Used for Potassium ⁽¹⁰⁾		
				Watt/(Cm ²)(C/Cm)	Btu/(Hr)(Ft ²)(F/Ft)	
0	32	0.47 ₆	27.5	--	--	--
100	212	0.50 ₇	29.2	0.47 ₄	27.4	+6.5
200	392	0.52 ₉	30.6	0.49 ₅	28.6	+6.4
300	572	0.54 ₈	31.6	0.51 ₄	29.7	+6.2
400	752	0.56 ₄	32.5	0.53 ₀	30.6	+6.0
500	932	0.57 ₈	33.4	0.54 ₆	31.6	+5.5
600	1112	0.59 ₂	34.2	0.56 ₀	32.4	+5.4
700	1292	0.60 ₃	34.8	0.57 ₄	33.2	+4.8
800	1472	0.61 ₅	35.5	0.58 ₈	34.0	+4.4
900	1652	0.62 ₆	36.2	0.60 ₁	34.7	+4.0
1000	1832	0.63 ₅	36.7	0.61 ₄	35.5	+3.3
1100	2012	0.64 ₄	37.2	0.62 ₇	36.2	+2.6
1150	2102			0.63 ₄	36.6	
1200	2192	0.65 ₃ (a)	37.7			

(a) Extrapolated.

TABLE 9. INTERPOLATED ELECTRICAL RESISTIVITY OF NB-1Zr ALLOY

Temperature, C F		Electrical Resistivity, microhm-cm		Difference, per cent of previous lot
		Present Lot Used for Cesium	Previous Lot Used for Potassium ⁽¹³⁾	
0	32	14.3	--	--
100	212	19.4	19.5	-0.52
200	392	23.8	23.7	+0.42
300	572	27.8	27.7	+0.36
400	752	31.6	31.4	+0.63
500	932	35.2	35.1	+0.28
600	1112	38.6	38.7	-0.26
700	1292	41.9	42.1	-0.48
800	1472	44.9	45.4	-1.11
900	1652	47.7	--	--
1000	1832	50.5	--	--
1100	2012	53.2	--	--
1200	2192	55.9	--	--

Table 9 shows interpolated electrical resistivity values for the two lots of Nb-1Zr alloy. The electrical resistivities are very nearly the same, which raises the interesting question of why the thermal conductivities are different while the electrical resistivities are similar. This results in different Wiedemann-Franz-Lorenz constants for the two lots of Nb-1Zr alloy.

A comparison of the structure and composition of the two lots of Nb-1Zr might resolve this matter, but this is beyond the scope of the present investigation.

VISCOSITY

(Elton H. Hall)

A part of the current Battelle program on the engineering properties of cesium has been the determination of the viscosity of liquid cesium from 35 to 1150 C.

The oscillating-cylinder method for liquid viscosity measurement was employed in this program. A closed hollow cylinder containing the cesium was suspended from a torsion wire and was permitted to oscillate about the axis of the suspension. The viscosity was calculated from the observed degree of damping of the cylinder's oscillation caused by the motion of the liquid contained within. This method was previously used for the determination of the viscosity of liquid potassium. The results of that study have been given in a previous topical report.⁽¹⁷⁾ Preliminary to that work, the viscosity of water was determined in the apparatus. Satisfactory agreement with literature values demonstrated the validity of the experimental technique and of the mathematical treatment of the data.

Literature Review

The viscosity of liquid cesium has been reported by Andrade and Dobbs⁽¹⁸⁾, who used the oscillating-sphere method. The cesium was contained in a glass sphere and the temperature range covered was reported as 28.4 to 210.9 C.

No other reported data on the viscosity of liquid cesium have been found.

Apparatus and Procedure

The same basic apparatus used to measure the viscosity of potassium was used for cesium. Details of the construction of the apparatus and a description of the experimental procedure were given in the report on the potassium viscosity.⁽¹⁷⁾ Unaltered aspects of the work will not be described again.

A new cylinder was machined from Nb-1Zr bar stock. The inside diameter was 1.5 inches, as before, but the walls were made 0.2 inch thick and the end plates 0.31 inch thick to safely withstand the somewhat higher vapor pressure of cesium. After final welding, the cylinder was vacuum annealed at 2125 F for 1-1/2 hours. No change was detected in the dimensions of the cylinder on annealing.

The moment of inertia of the assembled empty cylinder was determined as before. The mean of three measurements was 3255 g cm^2 . At the same time the period and residual damping of the empty system were determined with the cylinder at room temperature and at elevated temperature.

The equilibrium temperature of the cesium was measured by a calibrated Chromel-Alumel thermocouple placed in a well in the top of the cylinder. The leads from this thermocouple were free during equilibration and determination of the logarithmic decrement; they were contacted by external probes when a reading of this thermocouple output was desired. A check on the thermocouple calibration was obtained by making a time-temperature plot as the liquid cooled. A break in the curve with an extended horizontal section occurred as the liquid froze. The temperature indicated by the thermocouple at the horizontal portion was 28.5°C in good agreement with freezing point determinations made prior to loading.

Considerable effort was applied in an attempt to reduce the transverse motions which occur with the torsional oscillation. Both the influence of building vibrations and effects of starting the oscillation were considered. In order to isolate the apparatus more effectively from high-frequency building vibrations, a "soft" mounting was installed which gave the entire apparatus a low natural frequency. The new mounting consisted of supporting the frame from overhead I-beams by means of springs selected to support the load and give the desired frequency. With the feet completely free of the floor, building vibrations were very effectively isolated from the apparatus, as evidenced by the disappearance of the rapid "bow-string" motion which the cylinder suspension had commonly executed previously. However, the new support made the apparatus much more susceptible to other external influences such as air drafts. The final support was a compromise design in which the feet were adjusted until they were in light contact with a vibration isolation pad. This added much to the stability without reintroducing appreciable coupling to the floor.

The oscillation was started by the interaction of a magnetic field with a soft-iron rod attached to the suspension. In the previous work a pair of weak permanent magnets was used to provide the field. Inexact positioning of the magnets with respect to the iron rod exerts a lateral force on the suspension and a slight pendulum motion results. The substitution of Helmholtz coils for the hand-magnet operation did not improve the situation, so the limitations of the original method were accepted.

Data Reduction

The Shvidkovsky equation was again used to calculate the kinematic viscosity from the experimental data. The application of this equation is described in the report on potassium.⁽¹⁷⁾ A computer program was available for solving the equations.

Results and Discussion

The results of the computer solution of the Shvidkovsky equation for damping of liquid cesium at 21 different temperatures are given in Table 10. The values of the kinematic viscosity are obtained directly from the Shvidkovsky equation, while the

TABLE 10. VISCOSITY OF LIQUID CESIUM

t, C	ν , centistoke	ρ , g/cc	η , centipoise
289.4	0.277	1.715	0.476
341.5	0.239	1.685	0.403
290.2	0.270	1.715	0.462
407.0	0.211	1.648	0.347
144.2	0.328	1.790	0.588
457.3	0.208	1.619	0.338
206.7	0.330	1.760	0.580
489.5	0.186	1.599	0.298
97.6	0.418	1.812	0.757
762.2	0.178	1.428	0.255
71.8	0.540	1.823	0.984
713.5	0.165	1.458	0.240
551.3	0.199	1.560	0.311
853.2	0.148	1.370	0.203
799.0	0.142	1.404	0.199
603.5	0.185	1.528	0.282
554.2	0.190	1.560	0.296
1079.2	0.138	1.230	0.170
33.3	0.583	1.836	1.071
1130.8	0.159	1.182	0.191
1028.8	0.149	1.260	0.188

absolute viscosity is the product of the kinematic viscosity and the density as tabulated. The densities were obtained from the equation⁽¹¹⁾

$$\rho = \frac{1.84}{1 + 1.1755 \times 10^{-4} (T - 82.4) + 7.656 \times 10^{-8} (T - 82.4)^2} , \quad (9)$$

where ρ is in grams per cm³ and T is in degrees F.

The viscosity data are presented graphically as η vs. t in Figure 6. Also shown are the values obtained by Andrade and Dobbs.⁽¹⁸⁾ The data being reported are seen to be about 60 per cent higher than those of Andrade and Dobbs over the common temperature range.

A plot of the temperature dependence in the form of $\log \eta$ vs. reciprocal absolute temperature is shown in Figure 7. A striking similarity is seen between the temperature dependence of the cesium viscosity and that of potassium previously reported. The cesium data show more scatter, but the low-temperature points can be represented by a straight line within the indicated precision of each point. Above about 330 C the points fall below the line and a second straight line can be drawn to represent these points within the precision of most of the data. The solid lines in Figure 7 are the result of a least-squares fitting of the points to a straight-line equation in each region. The equations representing these lines are as follows:

303 to 600 K (30 to 327 C):

$$\log \eta = \frac{252}{T} - 2.785 , \quad (10)$$

with a standard deviation of ± 0.028 in $\log \eta$.

600 to 1423 K (327 to 1150 C):

$$\log \eta = \frac{400}{T} - 3.029 , \quad (11)$$

with a standard deviation of ± 0.026 in $\log \eta$.

Viscosity η is in poise and T is in degrees K. Conversion to engineering units leads to these equations:

545 to 1080 R (85 to 620 F):

$$\log \eta = \frac{454}{T} - 0.401 , \quad (12)$$

1080 to 2560 R (620 to 2100 F):

$$\log \eta = \frac{720}{T} - 0.645 . \quad (13)$$

Viscosity η is in pounds per foot-hour and T is in degrees Rankine.

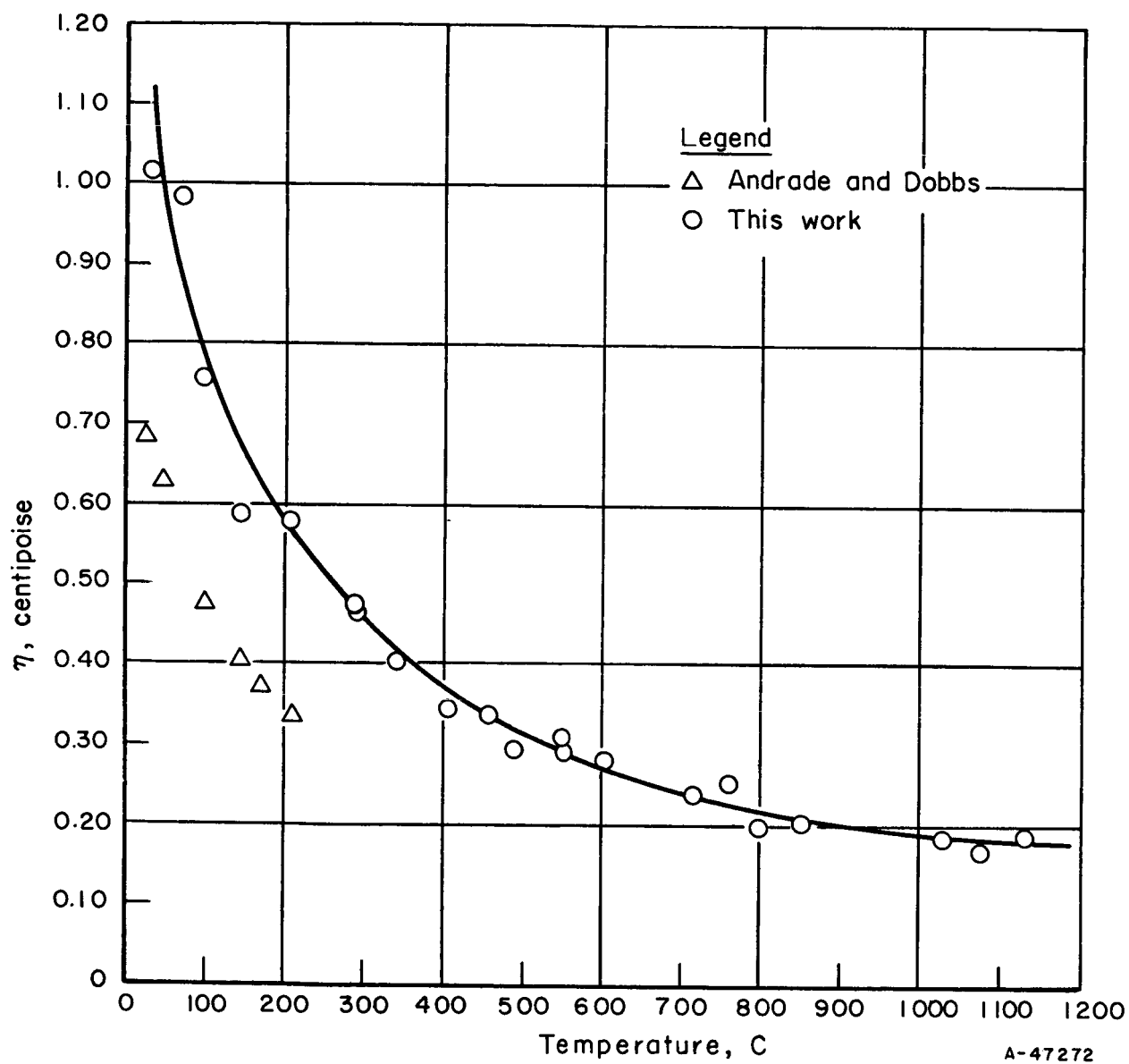
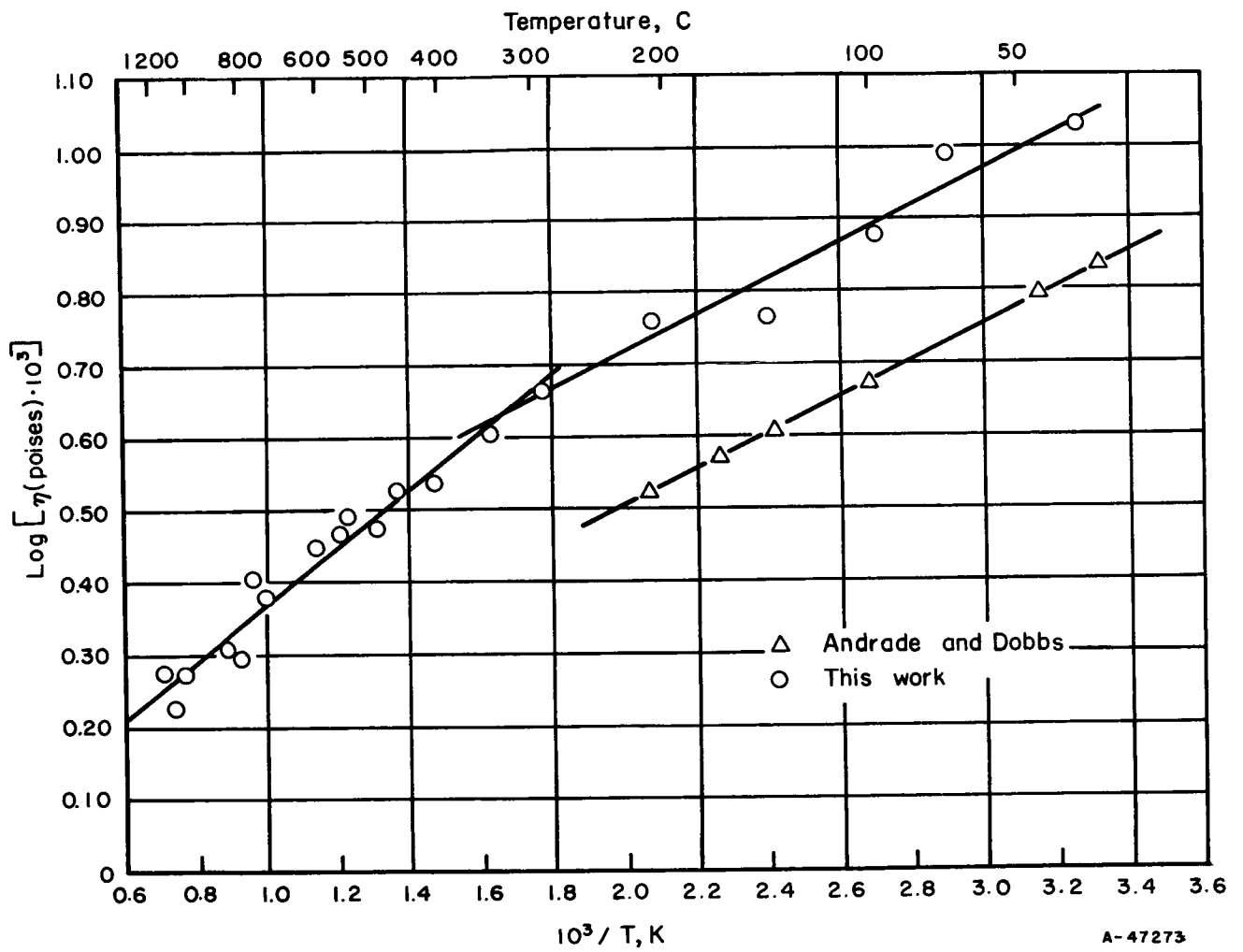


FIGURE 6. ABSOLUTE VISCOSITY OF LIQUID CESIUM



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FIGURE 7. LOGARITHMIC VISCOSITY PLOT

In comparing cesium and potassium, the intersection of the straight lines occurs in the same general temperature range (about 330 C for cesium and 370 C for potassium), and the differences between the slopes of the low-temperature line and high-temperature line are similar for both metals.

The greater scatter in the cesium data is believed to be due to the fact that smaller oscillation amplitudes (initial amplitude about 5 to 6 degrees) were employed than for the earlier potassium measurements (initial amplitudes 10 to 15 degrees). Smaller amplitudes were used because of difficulties in attaining a free swing at higher amplitudes in the cesium experiments. The small amount of pendulum-type motion that could not be eliminated thus represented a larger fraction of the oscillation amplitude and introduced a relatively larger error into the measurement of the cesium amplitudes and consequently of the decrements.

The reason for the significant disagreement between the data being reported and those of Andrade and Dobbs is not known. The latter data extrapolate to a melting-point viscosity which obeys the equation derived by Andrade. ⁽¹⁹⁾

$$\eta_M = K (A T_M)^{1/2} V^{-2/3} , \quad (14)$$

where

η_M = melting point viscosity

K = a constant

A = atomic weight

T_M = melting point

V = liquid atomic volume at the melting point.

This equation holds for the other alkali metals in addition to a number of other metals having a close-packed crystal structure. ⁽²⁰⁾ This fact strongly supports the Andrade and Dobbs data and indicates that the present data are in error. It should be noted that in Figure 7, the slope of the low-temperature line (0.252) is essentially equal to that for the data of Andrade and Dobbs (0.250). ⁽¹⁸⁾ This suggests that the error is a constant factor. No such factor can be located in the input to the computer or in the computer operation. The possible explanation that contamination of the cesium during transfer or by attack on the container material resulted in a higher viscosity for the sample under study is unlikely. Such contamination would not be expected to result in a constant factor error over a 200-degree temperature range. In addition, the freezing point curve obtained during the course of the viscosity measurements indicated that very little contamination had occurred.

One other factor suggests that the error was not associated with the sample itself. The unopened, potassium-filled cylinder was still on hand when the apparatus was re-activated. During preliminary checkout work before the new cesium cylinder was available, the potassium sample was installed. At one point the sample was heated and the damping roughly determined. It was high by a factor similar to the suspected error now apparent in the cesium measurements. Two possible explanations were considered: (1) contamination of the potassium sample had occurred during the several months of storage, and the actual viscosity of the contaminated sample was high; and (2) the

viscosity of the sample was unchanged but the wrong value of the decrement was obtained through some equipment malfunction or other cause. If the second possibility were true, the cause of the error would have to be rectified, while if the first possibility were true, measurements on cesium could begin without delay. It was judged that a definitive answer to the question of possible contamination of the potassium could not be obtained readily, if at all. Opening the cylinder under the best of conditions seemed certain to introduce contamination, hence subsequent examination or analysis of the sample would have to discriminate between sources of contamination. The apparatus was carefully checked and no malfunction could be found. Repeated rechecking of the apparatus did not appear to be warranted in the face of the uncertain condition of the sample. On these grounds it was decided to proceed with the cesium measurements. As the computer work was deferred until all the data could be run at once, the extent of the error was not apparent until the end of the program.

Extensive re-examination of the apparatus, procedure, and calculations was carried out after the computed results were noted. This included a new comparison of decrements determined optically with those determined at the same time by the electrical read-out system employed in the potassium and cesium measurements. No factor which could cause the observed viscosity to be high by a constant factor of the indicated magnitude could be found.

The present state of the viscosity data on liquid cesium is not clear. Although the present experimental data are subject to little doubt because of the care with which they were measured, the conflicting data of Andrade have indirect support from the melting-point viscosity correlation. Before the situation can be clarified, more direct evidence will be required.

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